SAWTEK
INCORPORATED

SAW DELAY LINES

Surface Acoustic Wave (SAW) delay lines provide accurate wideband delays in a smaller volume than most other types of delay lines because the acoustic propagation velocity is approximately 100,000 times slower than that of an electromagnetic wave. This makes SAW technology especially useful for several types of delay lines. The simplest SAW delay line configuration uses an input interdigital transducer (IDT) and an output IDT that are separated on the crystal surface by some distance that determines the amount of delay. (See Figure 1.) In fact, all SAW transversal bandpass filters are also delay lines, and similarly, SAW delay lines exhibit inherent bandpass characteristics.

The classes of SAW delay lines described in this brochure are non-dispersive, dispersive, and tapped. The simplest class is the non-dispersive SAW delay line which is used in oscillators, frequency discriminator circuits, and other signal processing applications.

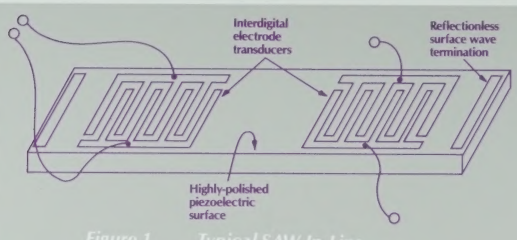
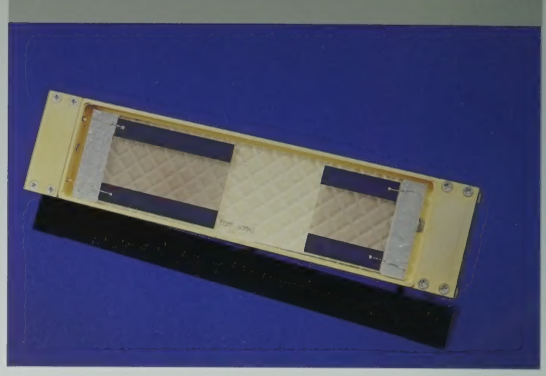


Figure 1. Typical SAW In-Line Transversal Filter or Delay Line Structure

Dispersive delay lines have the characteristic that the time delay varies according to frequency. This special type of frequency-modulated (FM) device is used most often in pulse expansion and compression for radar, signal analysis for EW receivers, and transform processing for programmable filtering functions.

Tapped delay lines can be viewed as an extension of the simple non-dispersive delay line. In this case, however, there is more than one output interdigital transducer (IDT). These types of devices can be utilized to produce a series of fixed delays. A tapped delay line can also be configured so that all of the output taps are connected together. If the phase of the output taps is varied according to a predetermined code, the device becomes a correlator. A typical waveform that is easily realized with a SAW correlator is a phase shift keyed (PSK) code which will be described in more detail later in this brochure.



Non-Dispersive Delay Lines

SAW non-dispersive delay lines can be implemented using non-dispersive IDTs or dispersive IDTs arranged in a manner in which the dispersion of the individual IDTs cancel. Non-dispersive IDTs are used when relatively narrow bandwidths (<30%) are required while dispersive IDTs allow the implementation of very large (<67%) fractional bandwidths with relatively low loss.

Although most non-dispersive delay lines are less than 20 μsec in length, Sawtek has developed a novel technique to implement very long delays with the result that devices with delays of up to 150 μsec in an area smaller than 2 x 2 inches are now available. A disadvantage of the very long delay lines is that the technique must use high coupling materials like lithium niobate with high temperature coefficients (see Table I). The minimum delay achievable is half the sum of the transducer time lengths plus a separation between the transducers to minimize crosstalk (rf feed-through). Since transducer length is usually inversely proportional to bandwidth, wider bandwidth delay lines can achieve shorter delays. A minimum delay of 250 nsec is recommended, even for very short transducers.

Sawtek can design and implement these delay lines with center frequencies from 10 to 1600 MHz. Other performance capabilities are summarized in Table II. Sawtek's SAW Filters brochure is a further resource that is also applicable to the non-dispersive delay lines.

Non-dispersive SAW delay lines are used in applications where long delays in a small volume are needed or where special signal processing requirements exist. Among these are:

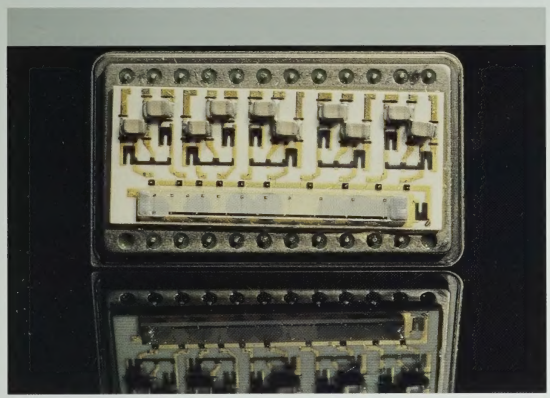
- Oscillator control
- Receiver discriminator circuits
- Radar signal processing/target simulation
- EW receivers
- Fixed-code generation or correlation for identification systems
- Spread-spectrum communications

Some of the above applications can also be implemented using other SAW technologies including resonators, dispersive delay lines, or convolvers. Sawtek will be pleased to discuss your particular delay line application and help select the optimum technical approach.

Tapped Delay Lines

The design of the basic delay line can be extended to include many output transducers of different delays to realize a tapped delay line. However, the implementation of a tapped delay line design can be more difficult due to internal reflections and crosstalk between the different IDTs. This problem becomes more acute as the number of taps increases. The best performance results are achieved by switching all the taps to ground when they are not used. Leaving taps open-circuited when not in use creates worst-case conditions.

Achievable performance for tapped delay lines of this type is very similar to that summarized in Table II for non-dispersive delay lines. The major difference is that achievable time spurious performance will be reduced as the number of taps increases or the tap spacing decreases.



A tapped delay line can also be configured so that all of the output taps are connected together. If the phase of the output taps is varied according to a certain code, this device is called a correlator.

Figure 2 shows the layout of a PSK correlator, in which the phase of each output tap has been designed for a particular phase shift keyed code. Even though this figure shows the phase shift as biphase (0° or 180°), the phase shift can also be quadriphase (0°, 90°, 180° or 270°) or have other configurations. Although many different code modulation schemes potentially exist, the most common code modulation for encoded SAW devices is phase modulation. If a modulation scheme such as MSK (minimum shift keying) is desired, it can be derived from the basic PSK code usually with the aid of only one extra SAW bandpass shaping filter. MSK modulation is sometimes preferred because of its inherently narrower spectral bandwidth. FSK and other codes are also possible.

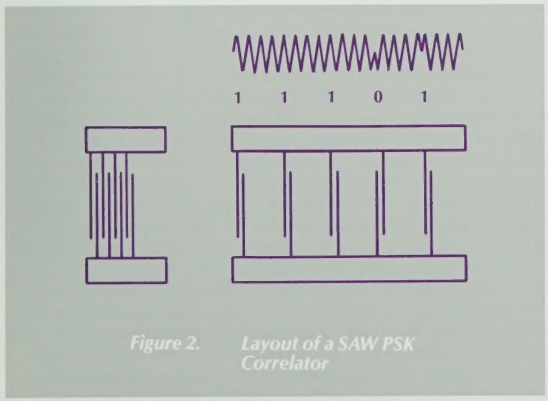


Figure 2. Layout of a SAW PSK Correlator

PSK devices (or other codes) can function much like dispersive delay ("chirp") devices. The PSK device can serve as an expander which expands a short impulse into a coded waveform with uniform amplitude over its time duration and as a compressor which compresses the coded signal from an expander in a time reversed code sequence to a short impulse with sidelobes as illustrated in Figure 3. The PSK device is most often used as a compressor since the phase-encoded signal can be easily generated by digital means.

A SAW PSK correlator consists of a wideband transducer that is nominally one-chip width (equivalent to one bit of the digital code modulating the rf carrier) in time length and a longer coded transducer. The taps of the coded transducer provide the time reverse of the input code sequence of the PSK waveform to be detected. The spacing between the taps is determined by the chip rate, or bandwidth, and the time length of the coded transducer will be equal to the number of taps, or bits, divided by the chip rate. When a PSK correlator is designed with the same center frequency, chip rate and code sequence as the reverse of the input code to be detected, a correlation peak with maximum amplitude will occur at the output after that code is applied at the input port. Typically, there is a small degradation from theoretical in the correlation peak amplitude due to temperature changes or manufacturing tolerances.

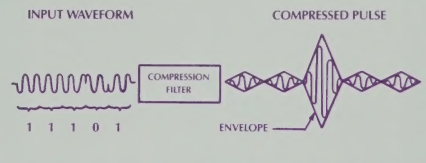


Figure 3. Five-Chip Barker Correlator Illustration

Figure 4a shows the correlation output of a 25-chip PSK correlator. Note that the sidelobe structure is very symmetric, confirming good amplitude and phase performance. The specifications of this device are:

Center Frequency	62.670 ± 0.008 MHz
Chip Frequency	5.2225 MHz
Number of chips	25
Delay Variation (−32°C to 71°C)	< 1 ns
Correlator Insertion Loss	< 30 dB
Processing Gain	> 12.4 dB
Sidelobe Level	< −20 dB

An interesting characteristic of these PSK devices is their spectral response. Figure 4b shows the frequency response of the preceding example from a network analyzer. The large variations in amplitude in the frequency domain are produced by the tapped/coded nature of the impulse response and are theoretically correct. This feature does pose a problem for CW insertion loss measurements, however.

SAW PSK correlators are widely used in spread-spectrum communication systems, phase-coded radars, radio data links, communication modems, navigation and identification systems, and range differencing surveillance systems. These devices offer the advantages of compact size, real-time processing, and asynchronous operation.

Table III lists Sawtek's capabilities for PSK devices. For other types of encoding, contact a SAW design engineer to discuss your requirement.

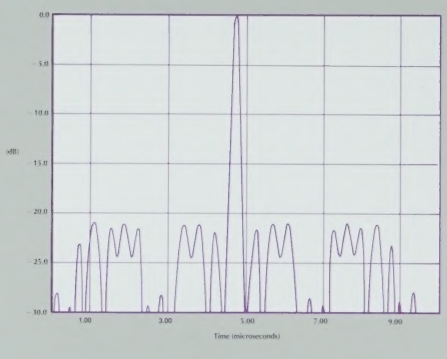


Figure 4a. Actual Correlation Output of the PSK Correlator

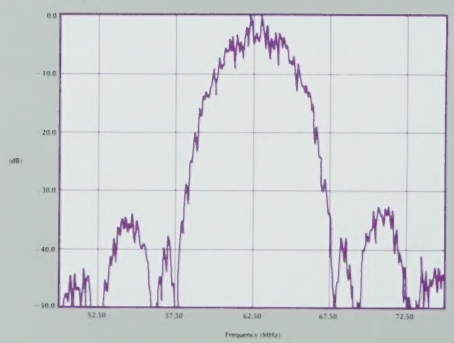


Figure 4b. Frequency Response of the PSK Correlator

SAW Dispersive Delay Lines

SAW dispersive delay lines are currently used most extensively in pulse compression radars. They provide a high degree of flexibility in the implementation of different types of waveforms which makes them suitable for the optimization of particular radar applications.

The basics of operation of a pulse compression system are illustrated in Figure 5. A short impulse is applied to the SAW expander to produce an expanded frequency-modulated signal at the output of the device (length T). The coding sense can be chosen to be up (high frequencies have longer delays than low frequencies) or down (high frequencies have shorter delays than low frequencies). After the expanded signal reflects off the target, it is received and fed into a SAW compressor having the complex conjugate frequency characteristic, or simply the impulse response time reverse, of the expander. Therefore, the delays encountered by the different frequencies are opposite to the delays in the expander network, resulting in all frequencies being compressed in time. Hence, the common terminology "expander" and "compressor" is used to describe a set of dispersive delay lines.

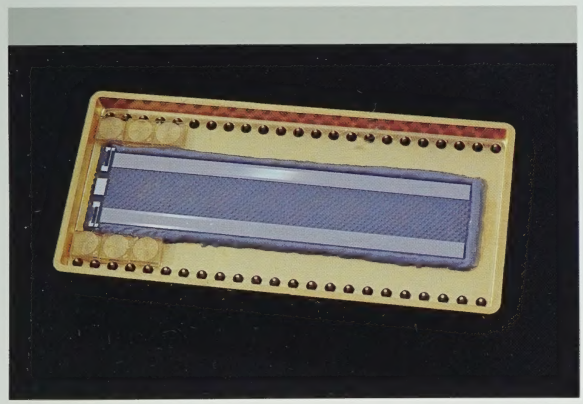
Since the delay experienced by a signal depends on its frequency, dispersive delay lines can also be used for spectral analysis. This type of application is most frequently found in EW receivers, but spectrum analyzers are used for other requirements as well. In addition, since the frequency information of a time domain signal can be displayed through this real-time spectral analysis, these components become the basic building blocks for an analog transform processor which can be used in programmable filtering, jamming suppression, and other novel signal processing applications.

The most important parameters of dispersive delay lines are usually specified in terms of the output signal with a specified input. The output time response of a compressor is characterized by a large compressed pulse at the center of a time interval of approximate length 2T that is the sum of the expanded signal length (T) and the compressor impulse response length (~T). On either side of the compressed pulse are time sidelobes that occur throughout the ± T interval. In most radar applications, these sidelobes should be suppressed as much as possible since they can be misinterpreted as extra targets. The compressed pulse width, or resolution, is generally measured at the 4 dB points and is typically 1.0 to 1.5 times the reciprocal of the chirp, or coded, bandwidth. The larger pulse width occurs due to the effects of reducing the sidelobe levels. Signal-to-noise improvement, or processing gain, is a measure both of the signal amplitude gain that is attributable to the pulse compression and of the reduction in competing noise. In the ideal matched filter case, maximum processing gain is the time bandwidth product (BT) of the system ($PG = 10 \cdot \log(B \cdot T)$). The achievable processing gain is sacrificed in some cases in order to reduce time sidelobe levels, however. A reduction

in signal-to-noise improvement compared to the ideal is called mismatch loss, or sensitivity loss, and is attributed to performance design trade-offs such as that for sidelobe levels and to other effects including implementation errors, manufacturing tolerances, Doppler shifts, and SAW second-order effects.

The design of the impulse response characteristics of the compressors and/or expanders is principally determined by these parameters plus external factors which include temperature and Doppler requirements. Usually the governing criteria is to achieve adequate sidelobe suppression. Sidelobes can be suppressed by applying amplitude weighting in the compressor (linear FM), phase weighting on both the expander and compressor (non-linear FM), or a combination of the two methods (modified non-linear FM). These three methods exhibit different performance advantages and disadvantages. For example, the effect of the different weighting mechanisms on mismatch loss and on worst-case time sidelobes vs. Doppler shifts is given in Figures 6a and 6b, respectively, for the three methods discussed here. These graphs illustrate the results for a set of dispersive devices with bandwidth of 3 MHz and time length of 30 μsec, a BT product of 90. A 45 dB Taylor window function was used for weighting. Although these results are typical, similar analysis should be performed for other parameter values.

Table IV summarizes these and many other important parameters and lists Sawtek capabilities for dispersive delay lines covered in this brochure.



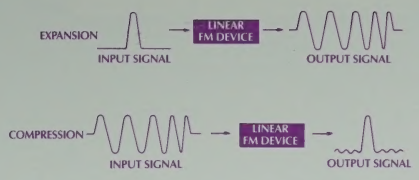


Figure 5. Basic Operation of a Pulse Compression System

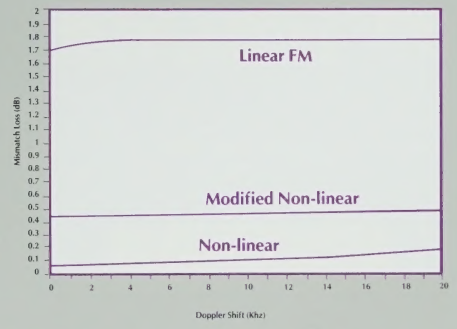


Figure 6a. Mismatch Loss versus Doppler

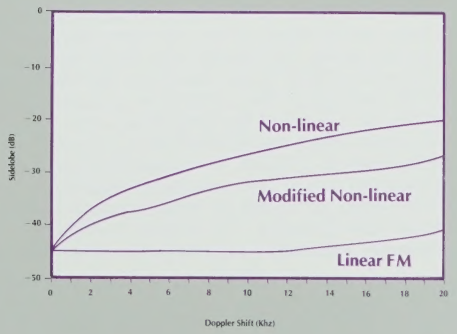


Figure 6b. Worst Sidelobe versus Doppler

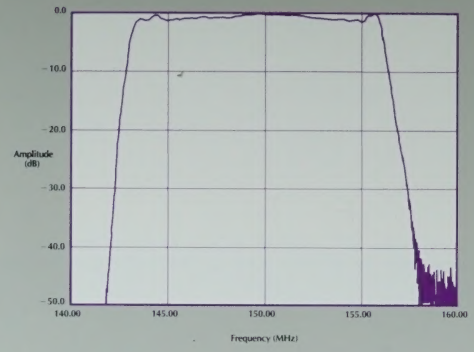


Figure 7a. Expander Spectrum

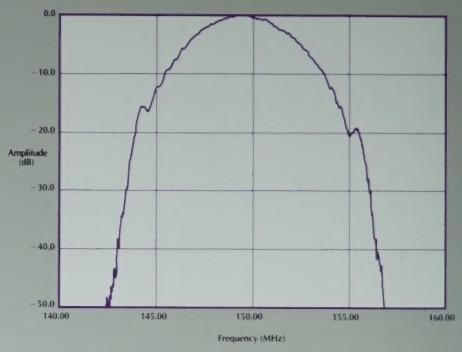


Figure 7b. Compressor Spectrum

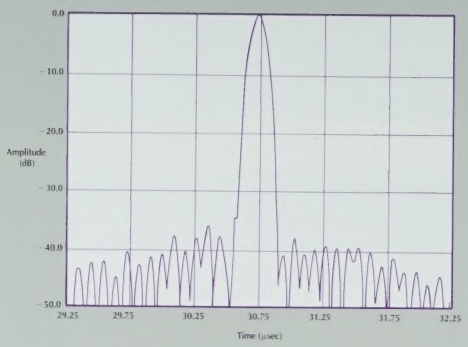


Figure 7c. Compressed Pulse (0 kHz Doppler)

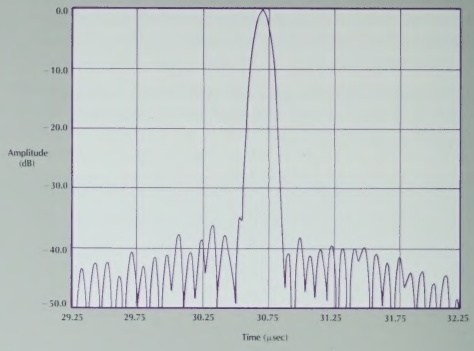


Figure 7d. Compressed Pulse (10 kHz Doppler)

Figure 7. Measured Performance for Linear FM Devices

Linear FM

The linear FM waveform is the most commonly used in present pulse compression systems. It is defined in the time domain by imposing the condition that the phase response be quadratic (linear group delay) and that the expanded pulse envelope be rectangular. This produces an almost rectangular passband for the expander. For the ideal matched filter case (maximum processing gain), the compressor passband would also be rectangular. Therefore, the compressed pulse and sidelobe pattern would follow the expected sin x/x response with peak sidelobe levels of -13.5 dB. To suppress the time sidelobes in a linear FM system, the compressor frequency response is weighted, or shaped, by applying one of many well-known window functions. The window function is entirely realized as amplitude weighting in the compressor.

Once the compressor is weighted, the expander and compressor are no longer a perfectly matched pair of filters and the optimum processing gain is reduced by an amount which depends on the weighting function employed. A typical value is 1.4 dB for a 45 dB Taylor window function. There is also a broadening of the pulse as the spectrum amplitude is narrowed by the weighting function with typical values between 1.3 and 1.5 times the reciprocal of the coded bandwidth.

Although the linear waveform suffers from a loss in processing gain, its advantage is very low sensitivity to Doppler shifts of the expanded signal. Typical Doppler effects include a time shift and broadening of the compressed pulse. Figures 6a and 6b show that both the mismatch loss and the worst time sidelobe change very slowly with Doppler shifts for linear FM.

The measured spectra of an expander and a compressor, together with the compressed pulse obtained, are shown in Figure 7. These devices have 3.83 MHz of coded bandwidth and are 25 μsec long. The expanded pulse was rectangular in time and nearly rectangular in frequency as seen in Figure 7a. The weighted compressor spectrum is shown in Figure 7b and the compressed pulse output in Figure 7c. The achieved sidelobe levels are 35 dB, the compressed pulsewidth is 0.36 μsec, and the mismatch loss is 1.3 dB. The effect of 10 kHz of Doppler shift shows negligible effects on the sidelobe level, as expected (see Figure 7d).

Non-Linear FM

One way of circumventing the processing gain degradation (mismatch loss) that results from the sidelobe suppression in linear FM systems is by equally splitting the window function between the expander and the compressor. In this manner, the mismatch loss is kept to a minimum (typical values are 0.1 to 0.2 dB) because the expander and compressor are an ideally matched pair. Unlike the linear FM case, the compressor has less significant amplitude weighting and the expander spectrum is no longer rectangular. The expanded pulse envelope must still be flat, however, so the delay response must be non-linear in order to achieve the weighting of the spectra.

The frequency response and compressed pulse characteristics of a 12.5 μsec, 13.6 MHz non-linear set of delay lines are shown in Figures 8a, 8b and 8c. The mismatch loss measured was 0.14 dB. The pulsewidth is 0.1 μsec and sidelobe levels are better than 40 dB. This system was designed for maximum processing gain.

The non-linear FM is not recommended, however, unless very low Doppler shifts are expected. This type of weighting leads to an increased sensitivity to Doppler effects, resulting in the appearance of a sidelobe at approximately (T/B) • Ds μsec away from the mainlobe. The level of this sidelobe depends on the Doppler offset (Ds [MHz]).

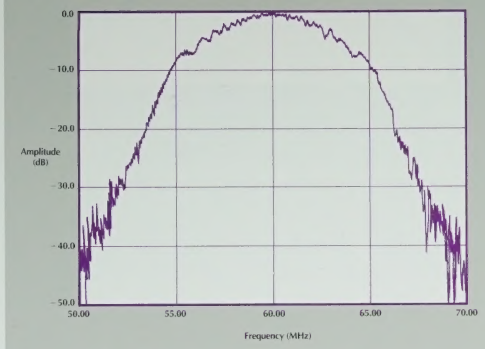


Figure 8a. Expander Spectrum

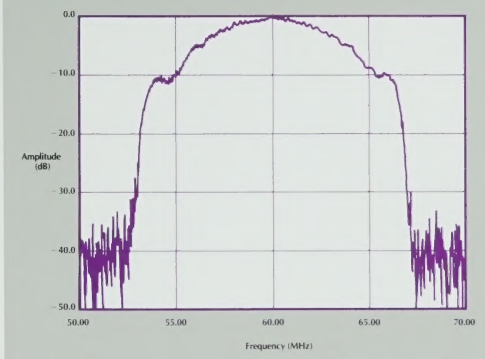


Figure 8b. Compressor Spectrum

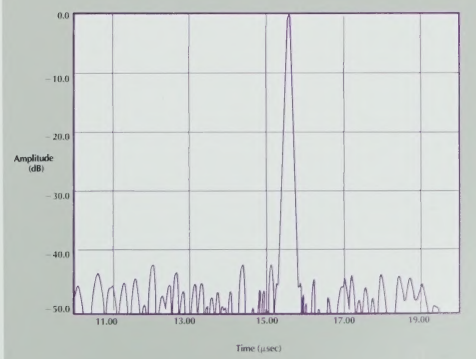


Figure 8c. Compressed Pulse (0 kHz Doppler)

Figure 8. Measured Performance for Non-linear FM Devices

Definitions and Parameter Clarifications

Tables II, III and IV list Sawtek's capabilities regarding important parameters needed in the specification of SAW delay line products. An important additional resource is Sawtek's SAW|Filters brochure which covers numerous other performance features for non-dispersive delay lines. You should also realize that it is not possible to optimize all parameters simultaneously in one delay line due to the interdependence of parameters. Selection of optimum performance parameters must be based on a thorough understanding of these complex relationships to maximize the advantages of SAW technology.

Center Frequency (F_0)

Highest performance is achieved for center frequencies below 500 MHz although Sawtek's design and production capabilities extend beyond 1 GHz for dispersive delay lines and 1.6 GHz for non-dispersive delay lines. For dispersive designs, the upper limits should be considered the sum of the center frequency plus half the bandwidth. For tapped delay lines including PSK correlators, we prefer the center frequency to be an integer multiple of the chip rate or bandwidth. Non-integer multiples can be accommodated at the expense of slight performance degradation.

Bandwidth (BW)

For dispersive devices, the bandwidth is regarded as the coded bandwidth rather than the 3 dB bandwidth of the spectrum. For PSK devices the bandwidth is the chip rate, or the reciprocal of the tap spacing. As long as the insertion loss is acceptable, it is usually desirable to use temperature-stable quartz substrates. For fractional bandwidths that are too large to achieve acceptable insertion loss on quartz, higher coupling materials such as lithium niobate may be used up to 67% fractional bandwidth. Ovens may be required to temperature stabilize some of these materials, however. See Table I for temperature coefficients of selected SAW substrates. Non-dispersive designs on quartz are usually restricted to fractional bandwidths less than 20%, but dispersive quartz designs (even in non-dispersive configurations) up to 50% are not unusual if 55 dB to 60 dB insertion loss can be accepted. Bandwidths larger than 25% on quartz or 40% on lithium niobate are almost certainly implemented using dispersive transducers.

Code

For PSK delay lines, any code sequence can be used and is specified by the user. For example, a code may be chosen because of its uniform sidelobe levels (e.g., Barker codes). For dispersive delay lines, refer to the discussion earlier in this brochure.

Pulse Length (T)

Pulse length usually refers to the time length of the expanded signal in a dispersive application.

Mismatch Loss

For pulse compression applications, mismatch loss is principally the reduction in signal-to-noise improvement due to the choice of weighting methods for sidelobe suppression. In both dispersive and PSK correlator applications, there is also mismatch loss contributed by effects which include temperature effects, frequency shifts, and manufacturing tolerances. For compressors, the mismatch loss is defined to be the difference in signal-to-noise improvement achieved and the ideal, $10 \cdot \log (B \cdot T)$. For PSK and other coded devices, the reference is not the ideal but rather the theoretical for a given code and selection of parameters.

Sidelobe Level Suppression

The sidelobe level is the amplitude ratio between the correlation peak and the highest sidelobe. For dispersive applications, the sidelobes can be divided into two categories:

1) Close-in sidelobes more than 30 dB below the peak of the compressed pulse are typical and better than 35 dB are frequently achieved. These sidelobes fall within 6 τ (τ being the 4 dB pulse width) and are primarily affected by Doppler effects in non-linear designs and slowly varying amplitude and phase errors.

2) Far-out sidelobes are usually below 40 dB and often reach 80 dB. These sidelobes are primarily affected by rapidly changing amplitude and phase errors. In cases in which the time bandwidth product is small (<50), gating sidelobes appear at $\pm$ T/2 which may prohibit the 40 dB suppression from being achievable. Sawtek has different techniques that will minimize these problems but final predicted performance will be given after a detailed analysis of the required specifications is complete. For tapped delay lines, the maximum sidelobe level achievable is dependent on the code sequence chosen.

Time Bandwidth Product (BT)

BT products as low as 20 can be realized that achieve good time sidelobe performance with Sawtek specialized design techniques. However, truncation effects in the SAW devices will produce higher gating sidelobes than in larger BT product designs. Typical upper limits are 3000 to 5000 with prototype capabilities up to 15000.

I/O Impedance

The nominal impedance of Sawtek dispersive delay lines is 50 ohms with a VSWR of 1.5:1 (maximum) achieved through impedance matching. This may be traded against insertion loss or other parameters. The matching may be internal to the hermetic SAW package or external to the SAW package on your PC board. Usually only one or two elements per port are required. Careful matching is generally more important in pulse compression systems to achieve optimum time sidelobe suppression.

Expander Signal-to-Noise Ratio

The signal-to-noise ratio is often significant to expansion systems because expander output signal levels are reduced not only by the device insertion loss but also by the expansion loss, $10 \cdot \log(B \cdot T)$.

Table I. SAW Delay Line Material Parameters

Material	Approximate Surface Wave Velocity	Temperature Dependency	Optimum Fractional Bandwidth for each Material
ST Quartz	0.124 in/μsec	$\frac{\Delta F}{F} = -(\frac{T-T_0}{5.4})^2$ppm	0.1% to 5%
Lithium Tantalate	0.129 in/μsec	−23ppm/°C	4% to 9%
YZ Lithium Niobate	0.134 in/μsec	−94 ppm/°C	7% to 30%
128° Lithium Niobate	0.153 in/μsec	−72 ppm/°C	15% to 67%

Table II. Performance Parameters for Sawtek Non-Dispersive Delay Lines

Center Frequency	10 to 1600 MHz	Phase Ripple	1 to 10 degrees
Fractional Bandwidth	0.1 to 67%	Group Delay Ripple	10 to 250 nsec
Delay	0.25 to 150 μsec	Triple-Transit Suppression	30 to 60 dB
Insertion loss	10 to 35 dB	Spurious Suppression	40 to 70 dB
Amplitude Ripple	0.1 to 1.0 dB	Temperature Dependence	See Table I

Table III. Performance Parameters for Sawtek PSK Delay Lines

Center Frequency	10 to 800 MHz	Spurious Suppression	40 to 70 dB
Fractional Bandwidth	2 to 40%	Sidelobe Level Degradation from Theoretical	< 1 to 3 dB
Insertion loss	20 to 50 dB		
Maximum Length	< 40 μsec	Processing Gain Degradation from Theoretical	< 1 to 3 dB
Chip Rate	< 200 MHz		
Triple-Transit Suppression	30 to 60 dB	Temperature Dependence	See Table I

Table IV. Performance Parameters for Sawtek Dispersive Delay Lines

Expander		Compressor	
Center Frequency	20 to 1000 MHz	Compressed Pulse Width (τ)	3 to 1000 nsec
Fractional Bandwidth	2 to 67%	Time Sidelobes	
Pulse Length	0.25 to 120 μsec	(Close In $\|t\| < 6\tau$)	< −30 dB to < −40 dB
Coding Type	LFM, NLFM, MNLFM	(Far Out $\|t\| > 6\tau$)	< −40 dB to < −45 dB
Code Sense	Up, Down	Mismatch Loss	0.1 to 2 dB
Amplitude Ripple of Expanded Pulse	± 0.25 dB to ± 0.5 dB	Signal-to-Noise Improvement	10 dB to 35 dB
S/N Ratio	*	Dynamic Range	*
I/O Impedance	50 ohms	I/O Impedance	50 ohms
VSWR	1.5:1	VSWR	1.5:1

* Consult factory

THE SAWTEK ADVANTAGE

Sawtek's stringent Quality Assurance program meets the exacting standards of military requirements. And because we apply the same demanding standards of quality used in our military programs to our commercial and consumer products, we can ensure product reliability for every SAW component we manufacture.

For those applications requiring specifications that deviate from those provided by any of our standard SAW products, we provide technical assistance and rapid response to custom design and production requirements.

Sawtek produces oscillators, resonators and resonator filters, bandpass filters, low-loss filters, delay lines, pulse expansion/compression assemblies, filter banks and modules. These components and subsystems are produced for both low-volume and high-volume programs in satellite communications, modems and information networks, radar, electronic warfare, cable television, security systems and other signal processing applications.

Sawtek is committed to on-time delivery of reliable SAW products at a very competitive price/performance ratio. So when your system demands the advantages of SAW technology – demand Sawtek!

FOR MORE INFORMATION

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